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This report describes research done on the basic physics of magnetic multilayers and microstructures. Among the problems studied were

1) Exchange Bias and Coercive Fields in Ferromagnet/Antiferromagnet Structures – we examined how these parameters depended on temperature and on surface roughness
2) Microwave Response of Microstructures – Filters and Phase Shifters. Here we looked at exchange-spring systems, mictrostrip and coplanar notch filters and phase shifters using metallic ferromagnets.
3) Damping Mechanisms in Ferromagnets – we developed a two-magnon scattering theory for damping which pays special attention to surface roughness.
4) Static and Dynamic Behavior of Dot Arrays - we showed that the hysteresis curves could be substantially modified by the lattice structure of a magnetic dot array.

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Statement of Major Problems Studied

1) Exchange Bias and Coercive Fields in Ferromagnet/Antiferromagnet Structures

The exchange biasing of ferromagnets by antiferromagnets has proved to be an important issue for magnetic data storage where it plays a key role in the biasing of GMR reading heads. In this structure a number of changes can occur to the hysteresis curve associated with the ferromagnet:

1) The hysteresis curve may be shifted so that it appears that the antiferromagnet produces an effective field acting on the ferromagnet. This field is typically a few hundred Gauss or less.

2) The width of the hysteresis curve can be substantially increased. The increase can extend to a few kG.

The precise mechanism for exchange biasing has remained unclear for over 40 years although substantial progress has been made recently. We investigated a number of different problems related to this issue. One concerned the temperature dependence of the bias field and of the coercive field. Obviously in practical applications thermal stability is a major issue and it is important to know how these parameters change with temperature. In addition we explored how interface roughness influences exchange biasing.

2) Microwave Response of Microstructures – Filters and Phase Shifters

In recent years there has been an interest in moving to higher frequencies (10-80 GHz) for radar applications. Magnetic materials such as Fe and Co are naturally of interest for work in this region because the spin waves in these materials have frequencies in this region. We investigated a number of different materials and material combinations in order to see whether these magnets would be suitable for high-frequency signal processing. These included the exchange-spring system of coupled magnets (Fe/SmCo) and magnetic/dielectric layered structures. In collaboration with Z. Celinski an experimentalist at the University of Colorado at Colorado Springs, a number of different proto-type devices (notch filters and phase shifters) were constructed using both Fe and permalloy as the active material. These structures were analyzed theoretically and measured experimentally.

3) Damping Mechanisms in Ferromagnets

Ferromagnetic resonance (FMR) linewidth is a key parameter that controls the microwave response of magnetic samples. It also has great practical importance. For example in spin reversal of magnetic memories it is desirable to suppress "ringing" of the magnetization after reversal, and this may be controlled by the dissipation process. In addition, the damping of spin waves is of fundamental importance for high frequency signal processing using magnetic materials since it controls absorption of energy. We studied damping mechanisms in ultrathin magnetic films with an emphasis on surface roughness.

4) Static and Dynamic Behavior of Dot Arrays

The last 20 years has seen an explosion of work in ultra-thin magnetic films. The properties of ultra-thin films are substantially different from those of bulk materials, and new technologies such as giant magnetoresistance have emerged based on these new materials. We recently explored theoretically the properties of reducing the geometry even further, i.e. from a thin film to an array of tiny magnetic dots.

Summary of Most Important Results

1) Exchange Bias and Coercive Fields in Ferromagnet/Antiferromagnet Structures

Our initial work showed that the coercive field and the exchange bias field should both decrease with temperature. We showed that the coercive field should change more rapidly with temperature compared to the bias field. This is in agreement with some recent experiments, however the experimental situation is not clear and other results have also been found.

In addition we also investigated how roughness at the surface of the antiferromagnet could influence both the bias field and the coercive field. We showed that roughness could enhance the bias and produce unique directions in the system. Further we studied how different types of roughness (single site roughness versus larger feature roughness) changes the bias field. We found that the key issue was the net moment of the impurity site and that large bias fields could be produces by rough surfaces.

Nearly all of the research in this area has a key parameter - the microscopic exchange coupling between the ferromagnet and antiferromagnet. Unfortunately this parameter remains largely unknown, primarily because of the masking effect of surface roughness. In contrast to most previous research we investigated the effect of the exchange coupling on the antiferromagnet rather than the ferromagnet. We were able to show theoretically that the interface coupling could be obtained from changes in the spin flop transition field in the antiferromagnet and that this result was largely independent of roughness.

We examined two additional problems in the ferromagnet/antiferromagnet system. One paper (Physical Review Letters) studied a "natural" ferromagnet/antiferromagnet system - fcc Fe grown on Cu. For very thin films (12 atomic layers or less) this system is a natural F/AF structure, but with the Fe being both the ferromagnet and the antiferromagnet. This system has very interesting properties - including a magnetization that can increase as temperature increases. We obtained a theoretical description for this effect and a way of understanding the antiferromagnetic phase transition seen in this material. A second paper studied coercivity in the ferromagnetic/antiferromagnetic structure and showed how there could be an increase in coercivity as the temperature increased. This surprising result actually occurs in some experiments!

2) Microwave Response of Microstructures – Filters and Phase Shifters

In collaboration with Argonne National Laboratory we examined an exchange-spring system (Fe/SmCo) where one ferromagnet (Fe) is coupled to another with high anisotropy (SmCo). We found that the SmCo produces a large effective field on the Fe and, for thin Fe films, dramatically shifts the natural resonance frequency. For example, a frequency of about 70 GHz was obtained for a 20 Angstrom film, while the frequency for a thick film was about 20 GHz.

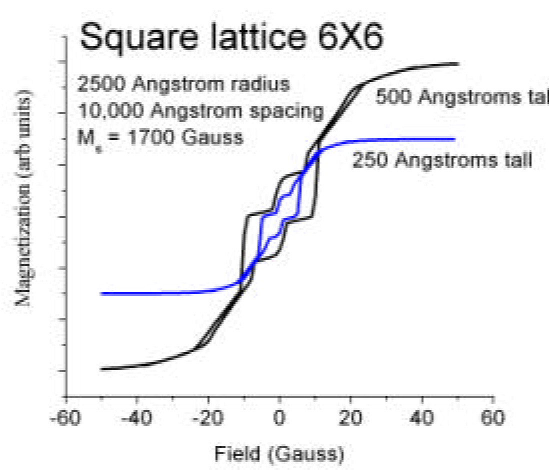
In collaboration with Z. Celinski we built, measured, an analyzed several prototype devices such as phase shifters and notch filters. Using Fe as the active element we built a microstrip notch filter which showed an attenuation of over 40 db/cm, in good agreement with theoretical calculations. We also investigated both experimentally and theoretically a new microwave filter design – a coplanar waveguide where are the elements of the filter lie in a plane. This is important because of ease of construction and testing and also because it allows modification of the impedance in a simple straightforward way. The structures tested included a notch filter and a phase shifter. Phase shifts of 450^{o} /cm were obtained.

3) Damping Mechanisms in Ferromagnets

We developed a new theory of extrinsic contributions to the FMR linewidths of ultrathin ferromagnetic films, with an emphasis on surface roughness as its origin. It was argued that a version of the two magnon mechanism invoked in the late fifties to explain the extrinsic linewidth in garnet crystals is also operative in ultrathin films, by virtue of the unique character of the contribution to the spin wave dispersion relation from dipolar interactions between spins in these quasi-two dimensional systems. We have recently extended this work to consider anisotropic magnetic materials and provide a generalized form for the damping term in bulk materials. Furthermore a careful comparison of experiment and theory for linewidths in ultrathin films and multilayers is underway with a publication to be expected in 2002.

We have recently extended this work to consider surface roughness in the form of steps which are parallel to each other and which make some angle with the magnetization. We find a striking result that depending on the geometry and on the applied magnetic field the linewidth should diverge! In real systems the linewidth divergence will no doubt be blunted because the strip edges and not all perfectly parallel or straight, however FMR studies of the azimuthal variation of linewidth should be very interesting.

4) Static and Dynamic Behavior of Dot Arrays



Our initial studies show that one can modify the macroscopic properties of the dot array by changing their microscopic structure. For example we find that the hysteresis curve for the dot array can be substantially changed by altering the lattice pattern of the array or simply by changing the height of the dots. An example of this is shown in the figure to the right. This could have important consequences in designing new materials for magnetic storage.

A particularly interesting result emerged in our calculations of the dynamics of an array of dots. We found that switching times (times for the magnetization reversal) could change significantly – by a factor of 3 - depending of the coupling between the dots. Since the coupling depends on the geometry of the dot array, one has again developed a substantial designable flexibility in the response of the material.

Papers Published under DAAG55-98-0294 (24 papers)

"Probing antiferromagnetic order in exchange-biased systems using heat capacity measurements"
Joo-Von Kim and R. E. Camley
Journal of Magnetism and Magnetic Materials, 240, 267 (2002)

"Annealing effects and degradation mechanism of NiFe/Cu GMR multilayers"
M. Hecker, D. Tietjen, H. Wendrock, M. Schneider, N. Cramer, L. Malkinsk, R.E.Camley, Z. Celinski
Journal of Magnetism and Magnetic Materials, 247, 62 (2002)

"Influence of interface coupling on spin-flop critical fields in ferromagnet-antiferromagnet coupled systems"
N. Cramer and R. E. Camley
Physical Review B – Rapid Communications, 63, 060404 (2001)

"Magnetization and susceptibility of ultrathin Fe films on Cu(100)"
R. E. Camley,
Journal of Applied Physics, 89, 7142 (2001)

"Temperature dependence of domain-wall bias and coercivity"
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Journal of Applied Physics, 89, 6913, (2001)

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M. Hecker, D. Tietjen, D. Elefant, C.M. Schneider, An Qiu, N. Cramer, R. E. Camley, and Z. Celinski
Journal of Applied Physics, 89, 7113, (2001)

"Incorporation of ferromagnetic metallic films in planar transmission lines for microwave device applications"
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IEEE Transactions on Magnetics , Volume: 37, 2392 (2001)

"Theory of spin excitations and the microwave response of cylindrical ferromagnetic nanowires"
Rodrigo Arias and D. L. Mills
Physical Review B 63 134439 (2001)

“High Attenuation Tunable Microwave Notch Filters Utilizing Ferromagnetic Resonance”
N. Cramer, D. Lucic, R. E. Camley and Z. Celinski
Journal of Applied Physics Vol 87 6911 (2000)

“Temperature Dependence of Exchange Biased Thin Films”
B. V. McGrath, R. E. Camley, Leonard Wee, Joo-Von Kim and R. L. Stamps
Journal of Applied Physics Vol 87 6430 (2000)

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Joo-Von Kim, R. L. Stamps, B. V. McGrath and R. E. Camley
Physical Review B Vol 61 8888 (2000)

“Theoretical Calculation of Magnetic Properties of Ultrathin Fe Films on Cu(100)”
R.E. Camley and Dongqi Li
Physical Review Letters, Volume 84, 4709 (2000)

“Extrinsic Contributions to the Ferromagnetic Resonance Response of Ultrathin Films”
Rodrigo Arias and D. L. Mills
Journal of Applied Physics, Volume 87, 5455 (2000)

"Magnetization dynamics: A study of the ferromagnet/antiferromagnet interface and exchange biasing". [invited paper]
R. E. Camley, B. V. McGrath, R. A. Astalos, R. L. Stamps. Joo-Von Kim and Leonard Wee
Journal of Vacuum Science and Technology Vol 17 p. 1335 (1999)

"Exchange Biasing in Ferromagnet/Antiferromagnet Fe/$KMnF_3$"
Z. Celinski, D. Lucic, N. Cramer, R. E. Camley, R. B. Goldfarb and D. Skrzypek
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"High-frequency response and reversal dynamics of two-dimensional magnetic dot arrays"
R. L. Stamps and R. E. Camley
Physical Review B 60 12264 (1999)

"Magnetization processes and reorientation transition for small magnetic dots"
R. L. Stamps and R. E. Camley
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M. Grimsditch, R. Camley, E. E. Fullerton, S. Jiang, S. D. Bader and C. H. Sowers
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Journal of Magn. and Magn. Materials 198-199 418 (1999)

"Magnetization dynamics in thin films and multilayers" [invited review article]
R. E. Camley
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"Phase transitions in magnetic multilayers; statics and dynamics"
D. L. Mills
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"Theory of roughness-induced anisotropy in ferromagnetic films: The dipolar mechanism"
R. Arias and D. L. Mills
Physical Review B vol.59, p. 11871-81 (1999)

"Extrinsic contributions to the ferromagnetic resonance response of ultrathin films
R. Arias and D. L. Mills
Physical Review B, vol.60, p. 7395-409 (1999)

Participating Scientific Personnel

At University of Colorado, Colorado Springs

R. E. Camley	Principal Investigator
R. L. Stamps	Post Doctoral Visitor
N. Cramer	MS earned during project
JV Kim	Visitor working on PhD
L. Wee	Visitor working on PhD
B. Kuanr	Post Doctoral Visitor

At University of California, Irvine

D. L. Mills	Principal Investigator
R. Arias	Visiting researcher
S. Rakhmanova	Post Doctoral researcher

Inventions Reported

none

Honors:

R. E. Camley received the LAS Research Award at University of Colorado Colorado Springs in 2000 and was named a President's Teaching Scholar (University of Colorado System) in 1999.